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## ► To cite this version:

Guillaume Beaumont, Angélique Drémeau, Ronan Fablet, Gaultier Real, Florent Le Courtois. AT-SEA EXPERIMENTAL EVALUATION OF THE INFLUENCE OF ENVIRONMENTAL FLUCTUATIONS ON THE ACOUSTIC COHERENCE RADIUS. Underwater Acoustics Conference, Jun 2019, Heraklion, Greece. hal-02330148

**HAL Id: hal-02330148**

**<https://hal.science/hal-02330148>**

Submitted on 29 Oct 2019

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# AT-SEA EXPERIMENTAL EVALUATION OF THE INFLUENCE OF ENVIRONMENTAL FLUCTUATIONS ON THE ACOUSTIC COHERENCE RADIUS

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**Abstract:** *Sound propagation in a fluctuating medium can be impacted by local space and time variation of the celerity. In the ocean, this environmental variability is mainly due to internal waves, tides or gyres and is well studied by oceanographers. More specifically, major research tackles the issue of characterizing the impact of these internal waves on a measured signal [1, 2, 3] propagated throughout the perturbed medium. One important quantity defined in this literature is the “coherence radius”: a metric that evaluates the distance between two sensors on which the received signals can be considered as correlated. It can be related to the level of spatial fluctuations under a high frequency approximation. Hence, integrated as prior knowledge on the propagating medium, the coherence radius can be very useful to determine the degree of corruption of a measured signal for typical inverse problems in underwater acoustics, such as tomography and source localization. In this work, we present different results from the analysis of the ALMA 2017 measurement campaign. ALMA (for Acoustic Laboratory for Marine Applications) is an autonomous acoustic observatory designed by DGA Naval Systems in 2012 and deployed in 2017 in the Saint-Florent Gulf, in the Western Mediterranean Sea. We specifically aim at assessing the intensity of environmental and acoustic fluctuations on sound waves propagated from a known source to a set of vertical line arrays and at comparing it to the theoretical predictions. Results suggest a strong relationship between the coherence radius and temperature fluctuations as well as other phenomena such as tides or water-mixing areas. Given hypotheses made about the influence of fluctuations on the radius of coherence, we further discuss future experimental settings to validate or discard these hypotheses.*

**Keywords:** *At-sea experiments, Internal Waves, Wave coherence, Fluctuating medium*

## 1. INTRODUCTION

Wave propagation through random media has been a raising topic of interest in the past few years. Common to many applications (e.g. aerial acoustics, RADAR, SONAR), the aim is to characterize the impact of a randomly fluctuating medium on a measured signal. This knowledge is essential to perform robust and reliable signal processing such as direction-of-arrival (DOA) estimations or to mitigate the degradation of the array gain [3].

In order to relate the environmental fluctuations to the propagation of sound waves, several formulations of “stochastic ocean” fluctuations were formulated in [1] and more recently [2], both corroborated by in-situ measurements. In this paper, we focus on a high-frequency formulation, leading to the definition of a particular quantity called “coherence radius” related to the mean size of the fluctuations in the medium.

In the interest of measuring and characterizing ocean variability, DGA Naval Systems conducted the design of a modurable underwater acoustic observatory, named ALMA (for Acoustic Laboratory for Marine Applications) [4]. Since 2014, the ALMA system is deployed each year and acquire data for this purpose [5]. In this paper, we focus on phases of the 2017 campaign and analyse the variability of quantities such as the coherence radius compared to the measurable variations of the propagation medium.

## 2. FOCUS ON THE 2017 ALMA CAMPAIGN

The 2017 experiment took place in the Gulf of Saint-Florent (Corsica) from the 3rd to the 13th of October. Here we focus on the phases involving the Passive Antenna (PA) and two emitters (S1&S2).

Two omnidirectional wideband pingers denoted S1 and S2 transmitted a controlled sequence. Every 3 minutes, both S1 and S2 emit the same sequence (see [5]). A 100 Hz positive frequency shift was applied to S2 for source separation purpose. The sequence is composed of 5 different signals : a Ricker pulse, a chirp, tone signals (from 1 to 13 kHz), multi-tonal signal and a white noise. The aim of such a sequence is to measure the impact of the corruption of the signal due to its propagation regarding the frequency of the signal.

These sources are immersed at different depths, 170 meters for S1 and 130 meters for S2 at the beginning of the campaign then at 50 meters depth.

The seabed follows a canyon topography, that implies great depth variations between the sources and the antenna (16 kilometers distant) and strong interaction between the variations of the seabed and the propagation medium.

### *Antenna*

The previous ALMA experiments introduced different usable array geometries. For this campaign, the geometry chosen is an vertical antenna composed with 32 uniform linear sub-antennas with a 15 cm sensor spacing [4] anchored at a depth of 140 meters. The antenna measures continuously during the phases involving the S1 & S2 emissions.

### *In-situ measurements of the variability: thermistor chain*

In order to measure the variability of the propagation medium, a thermistor chain is deployed and continuously records the temperature variations during the campaign. The thermistor chain is composed of 24 sensors on a 150 m array.

### 3. COHERENCE RADIUS OF THE SIGNAL

Characterizing the impact of stochastic fluctuations of the propagation medium on a measured signal is a challenging problem in underwater acoustics. Works initiated in [1] and pursued in [2] aim to define statistical properties of the signal perturbations. One of them relies on a high-frequency approximation of the emitted signal. Considering rays propagating along a perturbed path, this approximation assumes a Gaussian spread of micro-multipaths around a main “eigenray”.

Asymptotically, this leads to the so-called “simplified theory” (see [1]) which defines the theoretical value of the mutual coherence function (i.e. the normalized correlation function) between the  $n$ -th and the  $m$ -th sensors of an ULA:

$$|\Gamma_{mn}| = \exp\left(-\frac{1}{2} \frac{((m-n)\delta)^2}{R_c^2}\right) \quad (1)$$

with  $\delta$  the sensor spacing and  $R_c$  the coherence radius. In the literature [1,2],  $m$  and  $n$  the sensor indexes,  $R_c$  is a function of the mean perturbation of the propagation medium, the fluctuation spectrum and the frequency of the measured signal. A knowledge of this quantity allows us to put some hypotheses about the strength of the fluctuations and can be favorably exploited as prior information in DOA estimation schemes (see e.g. [6]).

To recover  $R_c$ , we confront (1) to an empirical estimation of the mutual coherence between the signals measured at the  $n$ -th and the  $m$ -th sensors (resp.  $Y_n$  and  $Y_m$ ), such as :

$$|\hat{\Gamma}_{mn}| = \left| \left\langle \frac{Y_n Y_m}{|Y_n| |Y_m|} \right\rangle_{N_s} \right| \quad (2)$$

Where  $N_s$  is the number of snapshots. With  $N_s$  large enough, we are able to identify the quantity  $R_c$  from  $|\hat{\Gamma}_{mn}|$  and observe the variations of this distance over time. For this calculation, we will consider  $N_s$  as the total number of detected samples at a given frequency at a given measurement phase.

### 4. COHERENCE RADIUS ESTIMATION

In this section, we will analyze the results of the 5th phase of the 2017 ALMA campaign. This phase started the 9th of October with a continuous emission of S1 and S2 had a duration of 3 hours and 40 minutes.

To process this phase, we identified the coherence radius using equations (1)-(2) for the multi-tonal sequences emitted by the sources. The interest of these signal lies in the fact that by filtering the signal at a given frequency we can observe the variations of the received signal at different frequencies subject to the same fluctuations.

Figure 1 represents the mutual coherence function for the lowest frequencies emitted by S1, as a function of the distance between two sensors (namely, as a function of  $\delta_z = (m-n)\delta$ , with  $(m, n)$  indices of two different sensors).

We observe here a decrease of the coherence radius with the frequency, confirming the theoretical model defined by [1,2].

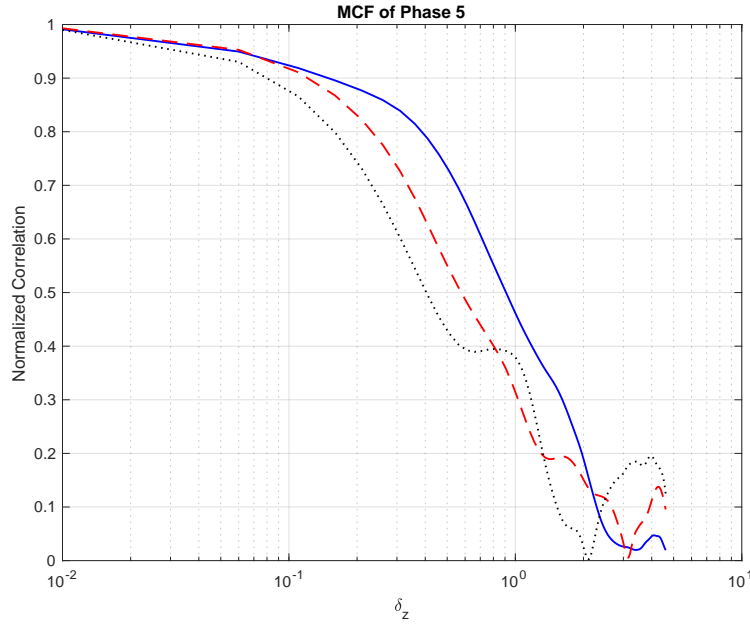


Figure 1: Mutual coherence function for 1kHz (in blue solid line), 2kHz (in red dashed line) and 5kHz (in black dotted line). We observe the decrease of the correlation distance with an increase of the frequency.

#### A time varying radius of coherence

For this phase, another interesting result is the evolution of the coherence radius. Its periodicity is indeed synchronized with the semi-diurnal tide. Figure 3 presents the tide chart of Centuri near the experiment area.

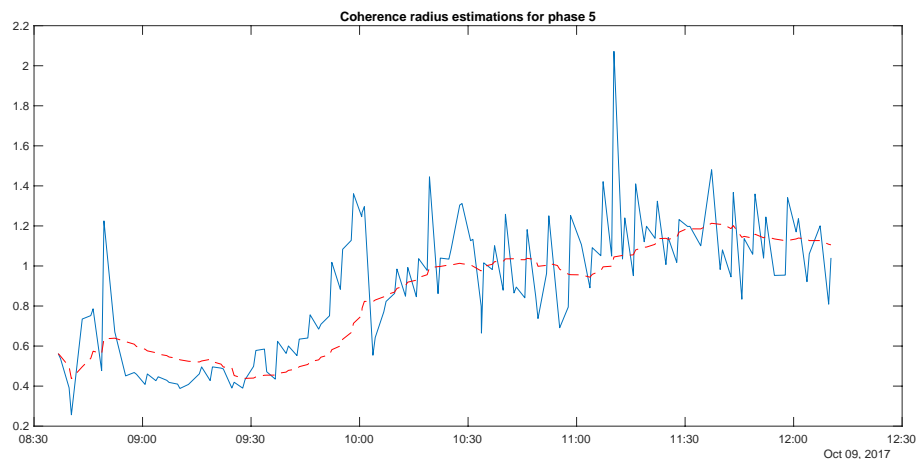


Figure 2: Evolution of the estimated coherence radius during the phase 5 for 1 kHz. The continuous line represent the coherence radius estimation while the dashed line represent its moving average.

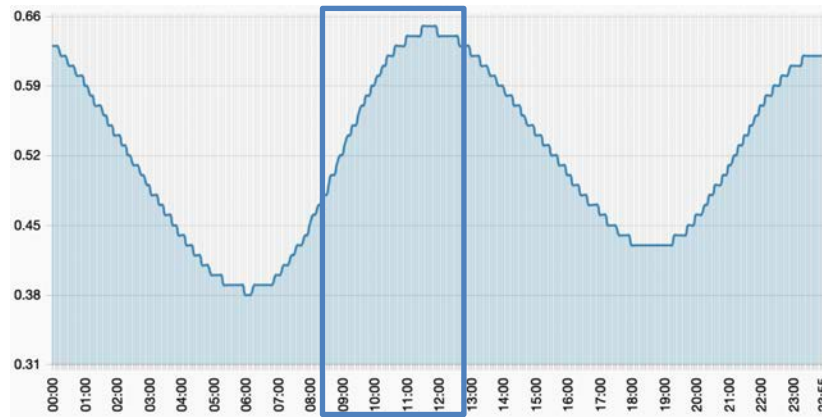


Figure 3 : Evolution of the tide at Centuri in the 9th of October, with a highlight on the tide for the 5-th phase (source [maree.shom.fr](http://maree.shom.fr)).

Confronting figures 2 and 3 tends to underline the dependency of the coherence radius on a phenomenon essentially driven by a semi-diurnal tide component. However, this observation does not explain the entire behavior of the evolution of the coherence radius. Other low frequency phenomena and a high frequency noise seem indeed to be involved. In the next subsection, we try to highlight the presence of other internal waves as major contributors to the variations of  $R_c$ .

#### *In-situ measurement of internal waves*

Internal waves, as the result of circulation of fluids excited by gravity waves, provoke turbulent mixing. Observing and quantifying them can thus be done by measuring the thermal mixing through the thermistor chain.

The bottom sub-figure of Figure 4 is the power density spectrum of the temperature measurement for the entire campaign on the last sensor (i.e. the deepest sensor of the chain). We can observe an important quantity of energy related to high-frequency phenomena which can be related to waves and bathymetry-induced mixing. Moreover, some low-frequency peaks correspond to diurnal (M2, S2 & N2) gravity waves. These results highlight the presence of gravity-induced internal waves in the experiment. According to the Munk classification of internal waves [7], the PSD (for Power Density Spectrum) of the temperature measurements allows us to identify the presence of long-period waves and infra-gravity waves in the environment.

## 5. ANALYSIS OF LONGER PHASES

In order to find a true relationship between the variations of the coherence radius and the measured fluctuations of the propagation medium, more phases of the ALMA campaign have been analyzed. Due to the long period of the signals of interest, longer phases were evaluated.

The following phases are the 12th, 13th and 14th phases, with durations of 12 hours approximatively for each phase. We expect to observe a periodic variability of the coherence radius with a higher precision than in our previous study.

Because they are contiguous, an analysis of both phases can be done by visualizing the PDS of the coherence radius regarding the PDS of temperature variations.

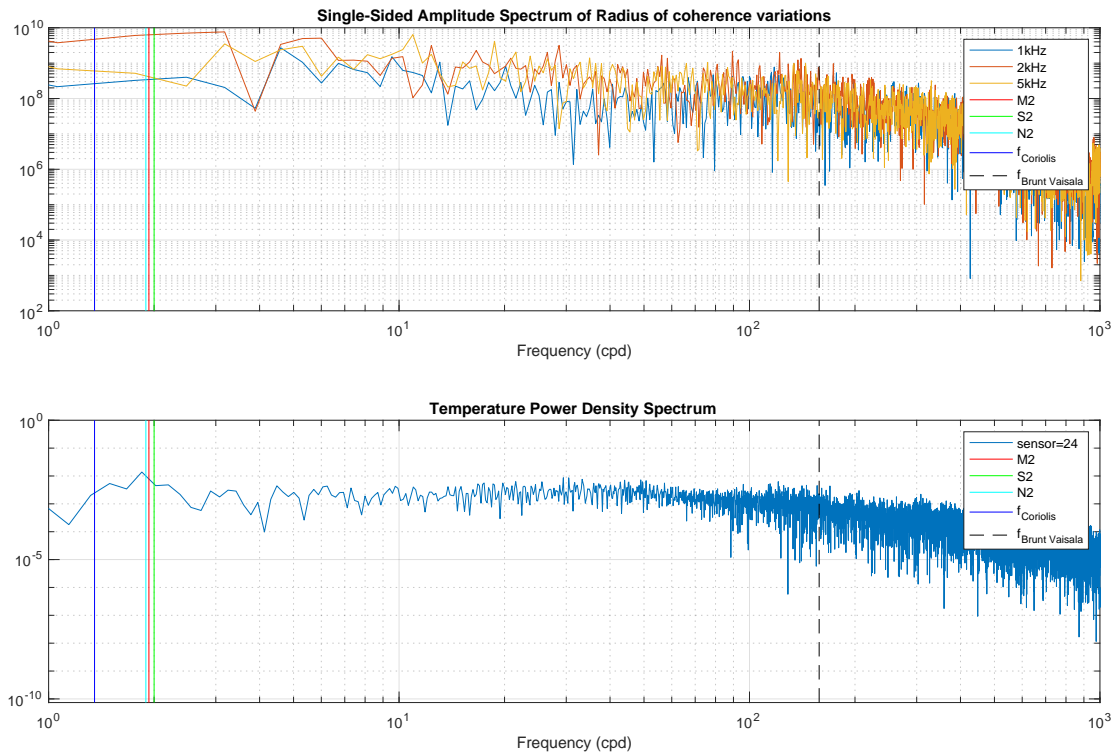


Figure 4: Comparison of the variation spectrum of the coherence radius for the 3 lowest frequencies of the ALMA sequence (top) and the temperature measured by the thermistor chain (bottom).

Figure 4 highlights similarities between the spectrum of temperature variations and the spectrum of coherence radius variations. Indeed, especially at low frequencies, the trend of the coherence radius variations follows the temperature spectrum. Moreover, we can notice similar lobes in the spectrum in the low frequencies domain of Figure 4 (more precisely the local maximum at 5 and 10 cpd and local minimum at 4 cpd) showing a possible measurability of the internal wave spectrum using the coherence radius estimation. However, the temporal resolution of the measurement (driven by the sequences emitted by S1 and S2) does not allow us to draw any strong conclusion on the impact of the temperature variations on the coherence of a measured signal.

## 6. CONCLUSION

Useful for antenna processing application like array gain compensation or adaptative processing for DOA estimation, the estimation of the radius of coherence of the signal is a complex issue due to the fact that this quantity varies with the propagation environment.

In this work, we have observed with long-duration measurements a strong correlation of the spectrum of the variations of temperatures in the water column and the variations of the

coherence radius spectrum. More generally, we have provided elements to identify measurable quantities influencing these variations. Such elements are of interest to proceed to a rapid assessment of the fluctuations of the environment and the coherence radius. They can then be used as reliable prior information for signal processing tools.

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